ELECTRON LOSS RATE FROM THE OUTER RADIATION BELT

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Abstract: The rate of loss of electrons from the outer radiation belt is obtained by using recent electron flux measurements on Discoverer satellites and assuming the coulomb scattering dominates as the loss process. This results in an average lifetime of the order of 100 years for outer belt electrons.

Резюме: Скорость утечки электронов из внешнего радиационного пояса на основании недавних измерений электронного потока с помощью спутников Дискаверер определена в предположении, что в процессе утечки электронов основную роль играет кулоновское рассеяние. Таким образом найдено, что среднее время нахождения электронов во внешнем радиационном поясе – порядка 100 лет.

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1. Introduction

In this report we will consider the method and rate at which high energy electrons are lost from the outer radiation belt.

There is enough experimental information available now so that a reasonable picture can be formed of the electrons in the outer belt. From Explorer XII we now know there are typically $\sim 10^7$ electrons/cm^2 sec in the energy region 40 keV–1 MeV in the outer belt [1]. This is a considerably lower flux than earlier estimates had given. The flux does not vary much with position in the outer belt from 25 000 km to 65 000 km and also that flux does not vary much with time. Time variations of $\times 2$ or $\times 3$ in intensity are seen in the 100 keV energy range occasionally ranging up to $\times 5$ or $\times 7$ during August and September, 1961 [2]. These variations might be due only to changes in the magnetic field and the associated effects on particles rather than changes in the particle population. The large time variations in flux seen on several earlier experiments are seen only in the high energy ($E > 1.6$ MeV) group of electrons on Explorer XII. Very likely the large time variations on several earlier experiments involved the high energy electrons also.

At the times of magnetic storms the 100 keV flux increases by factors up to seven, but returns to roughly the pre-storm flux in a few days at the end of the storm [2]. All of these features seem to indicate a population of particles that has a quite long lifetime.

It is very important to a complete understanding of the radiation belt to know the lifetime of the trapped particles. When dealing with a steady state population, the only way to easily determine particle lifetimes is by measuring the loss rate from the belt. Knowing the total population of the belt then yields the average lifetime.

2. Data from experiments on Discoverer satellites

We have now information that bears on the lifetime of outer belt electrons in the 100 keV–1 MeV energy range. Several instruments have recently been flown on Discoverer satellites. These vehicles orbit at a few hundred kilometers altitude at an inclination of $\sim 82°$, so the earth is quite well covered by measurements from these satellites. The instruments that have been flown are: (1) a thin CsI scintillator covered by 2 mils of Be. This counted electrons of $E_e > 100$ keV and protons above about 3 MeV, (2) a thick plastic scintillator that counted electrons of $E_e > 2$ MeV and protons of $E_p > 15$ MeV, and (3) a ten channel magnetic electron spectrometer [3] that counted electrons from 80 keV to 1.25 MeV.

The count rates of the CsI detector are shown in fig. 1 for the Southern Hemisphere. Three types of features are seen here. First, off the coast of Brazil a high count rate is observed which is related to the loss of particles from the inner radiation belt. In this region the earth's surface magnetic field is weak, so that the inner belt particles come closest to the earth here. Secondly, irregular pulses of particles are seen in the auroral zones. From the electron spectrometer we know that these particles are electrons of $E_e < 200$ keV and a considerable fraction of them come essentially directly down the field lines. That is, the electrons are not trapped and drifting down in altitude, but rather, they are on their way to earth in one single bounce.

The third group of particles is the most interesting. About 10° or 15° subauroral in the South Atlantic we see a large population of particles. These particles are not uniquely identified as electrons, but no protons of $E > 3$ MeV are known to exist in this region of space, so they are almost certainly electrons. These particles show a reasonably consistent spatial distribution from pass to pass. They are the leakage from the outer radiation belt being lost in the Capetown Anomaly [4]. They showed a roll modulation when one of the Discoverer vehicles tumbled indicating they are almost certainly trapped particles. These particles were slowly being lost in an orderly way, quite different from auroral particles which are lost in squirts.

The plastic scintillator shows quite similar behavior in the Southern Hemisphere (fig. 2). The losses from the inner belt off Brazil and the loss from the outer belt off Capetown are quite apparent. The auroral spikes are, however, not seen indicating that the auroral particles are below the threshold of this detector.

In the Northern Hemisphere the Discoverer results are quite different. Auroral pulses are seen by the CsI detector (fig. 3) but the other features are not. The scintillator count rate (see fig. 4) does not show any high count rate regions as in the South Atlantic. Count rate contours for the high count rate regions in the South Atlantic are shown on figs. 5 and 6 for the two detectors.

These features of the radiation belts were first seen on low altitude Soviet satellites [5, 6]. Vernov *et al.* observed both the high intensity region off Brazil that they identified as mostly protons and related to the inner belt [5] and also a high intensity region in the South Atlantic identified as mostly electrons related to the outer radiation belt [6].

3. Calculation of the loss rate

From these low altitude measurements on the outer belt electrons, we can calculate the rate of loss of particles from the radiation belt. Cladis and Dessler [7] suggested studying the bremsstrahlung of electrons in the atmosphere in the region of the Capetown magnetic anomaly to get the loss rate from the belt. This present study uses the more direct method of observing the electrons directly. If we have steady state in the radiation belt, then the situation depicted in fig. 7 occurs. Particles are continually injected into the belt. If, as is commonly thought, radial diffusion is a slow process, then the particles are lost from the belt down into the atmosphere as shown in fig. 7. This loss rate can be described in terms of a motion of particles down into the loss cones eventually striking the earth.

In this calculation of the loss rate, we must assume that coulomb scattering is the dominant loss process. We have measured the particle flux Φ at altitude h. From this we can get the net motion of particles downwards, the drift flux, D, by

$$D = \left(\frac{\Phi}{v}\right) U$$

where v is the particle's velocity and U is a downward "drift velocity".

The drift velocity U describes the process of particles gradually leaking out the loss cone as the result of coulomb scattering. This is, of course, an average concept and any one particle does not smoothly move downwards in altitude. The first attempts to describe this loss process [8, 9] introduced

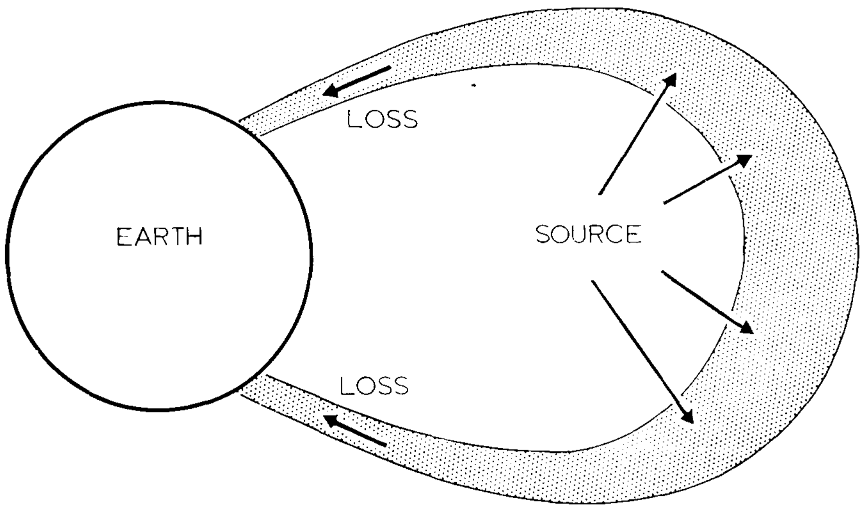

Fig. 7. The steady state picture of the radiation belt. Particles are injected into the belt at a rate s which must equal the loss rate l.

the concept of the velocity of lowering of mirror points, W. Later it was shown that this description of the process was incomplete [10] and a second term Y was needed which would describe the diffusion of the particles. McDonald has shown [11] that for the case of the exponential atmosphere the two terms can be written as

$$U = W + Y = W\left[1 + \frac{H}{\Phi\varrho}\frac{\partial}{\partial h}(\Phi\varrho)\right]$$

where H = scale height of the atmosphere and ϱ = air density.

If the electron flux Φ varies inversely with air density ϱ then $Y = 0$. We know that this situation is roughly true for protons, but there is no good data on electrons to evaluate Y. For lack of better information we will take $W = Y$ and $U = 2W$. It would be quite surprising if the altitude dependence of Φ were such that $Y \gg W$, but we must wait for final information on this.

Using the value of $U = 1.5 \times 10^5$ cm/sec for $E = 200$ keV for 400 km altitude, we can obtain D as a function of position from the CsI detector data. From

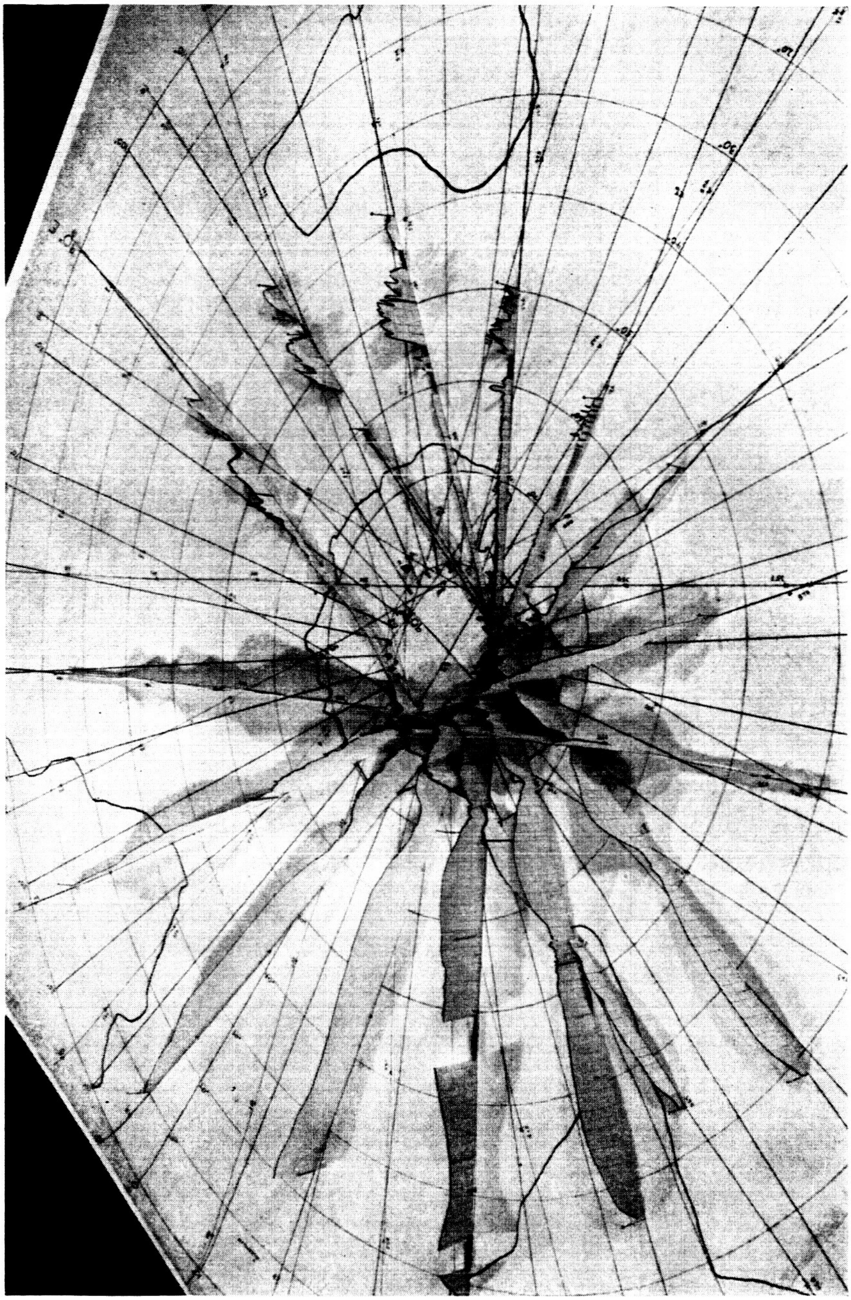

Fig. 1. Count rates of the CsI detector on Discoverer 31 in the Southern Hemisphere. The height of the strip gives the logarithm to the base 10 of the count rate at different positions. The highest count rate is above 10^4 counts/sec and the lowest count rate is about 10 counts/sec.

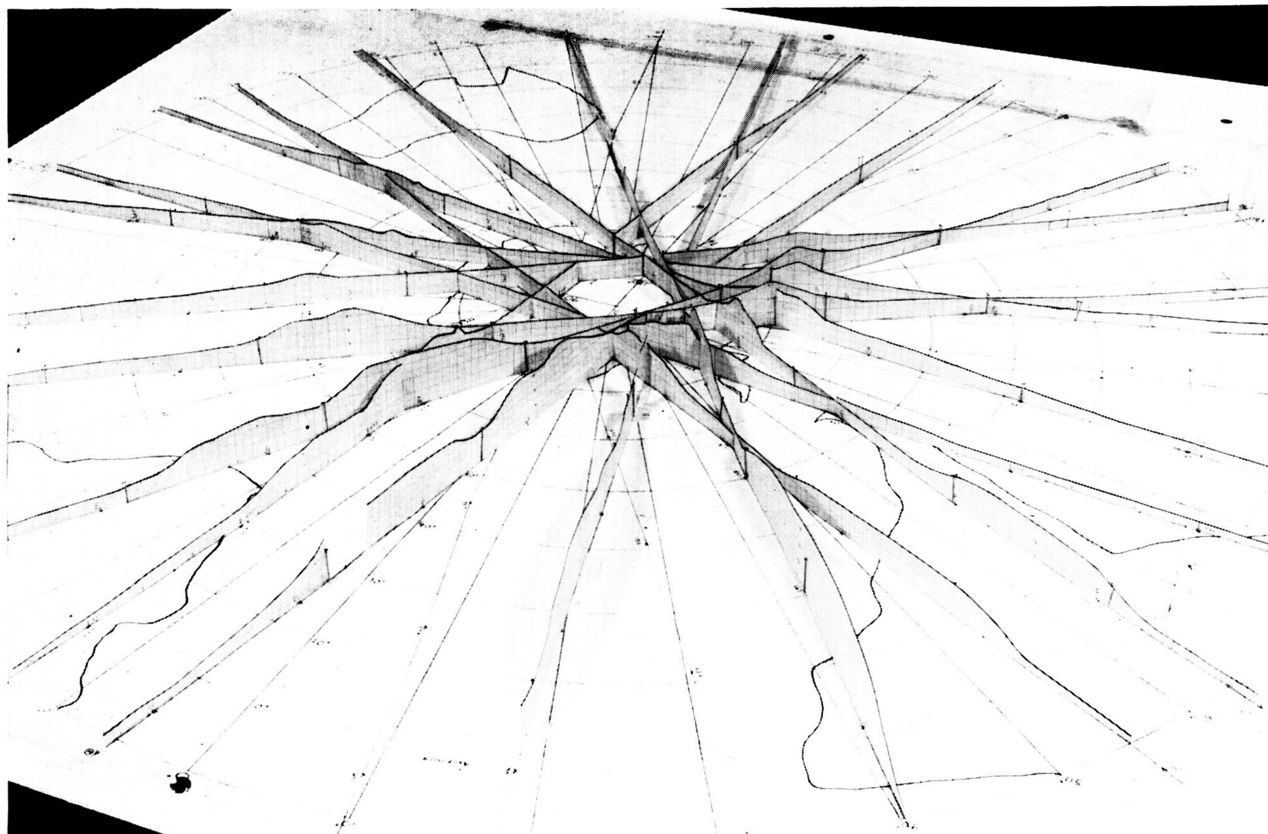

Fig. 2. Count rates of the plastic scintillator on Discoverer 31 in the Southern Hemisphere — same logarithmic scale.

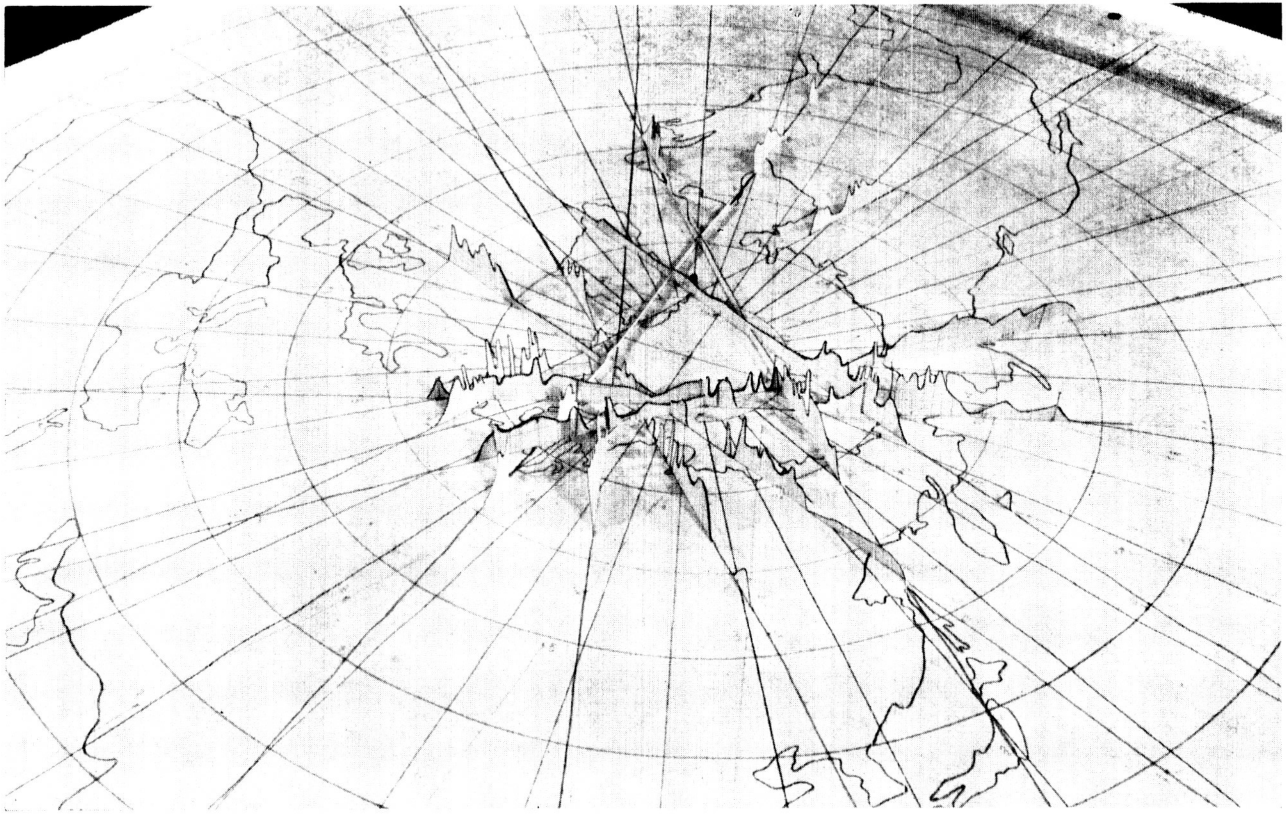

Fig. 3. Count rate of the CsI detector on Discoverer 31 in the Northern Hemisphere — same logarithmic scale.

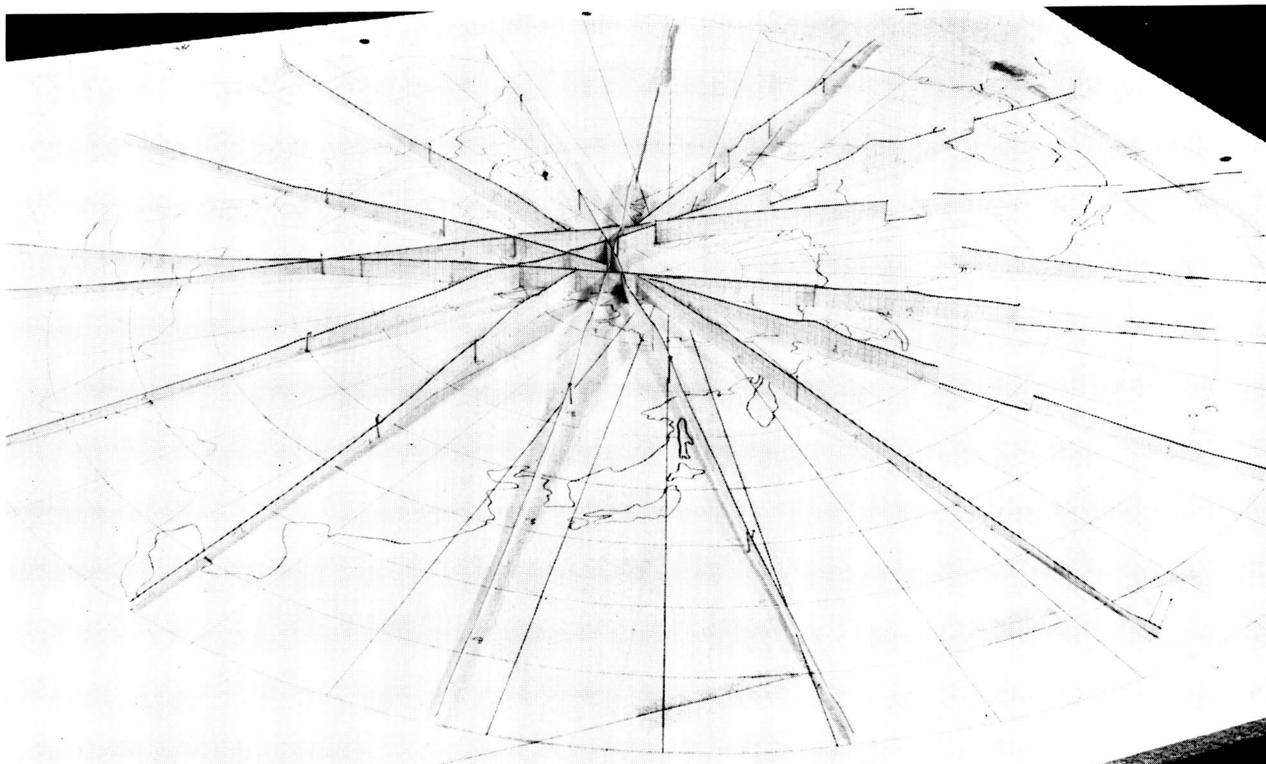

Fig. 4. Count rate of the plastic scintillator on Discoverer 31 in the Northern Hemisphere — same logarithmic scale.

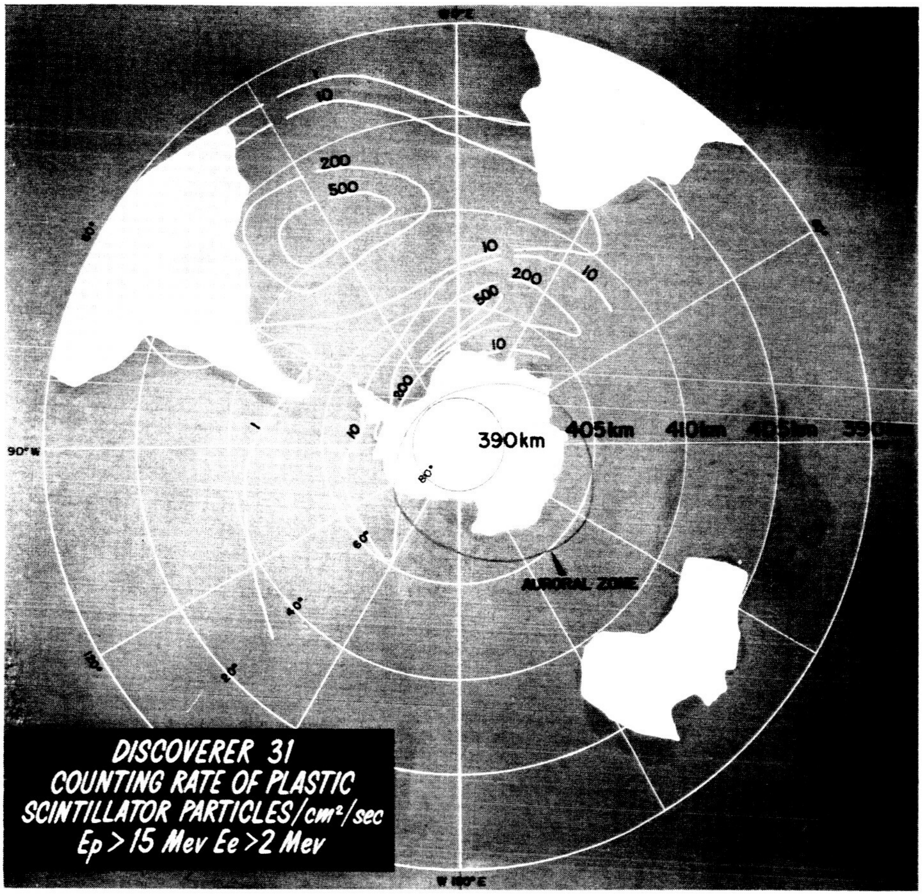

Fig. 5. Count rate contours for the plastic scintillator on Discoverer 31 for the Southern Hemisphere.

Fig. 6. Count rate contours for the CsI detector on Discoverer 31 for the Southern Hemisphere.

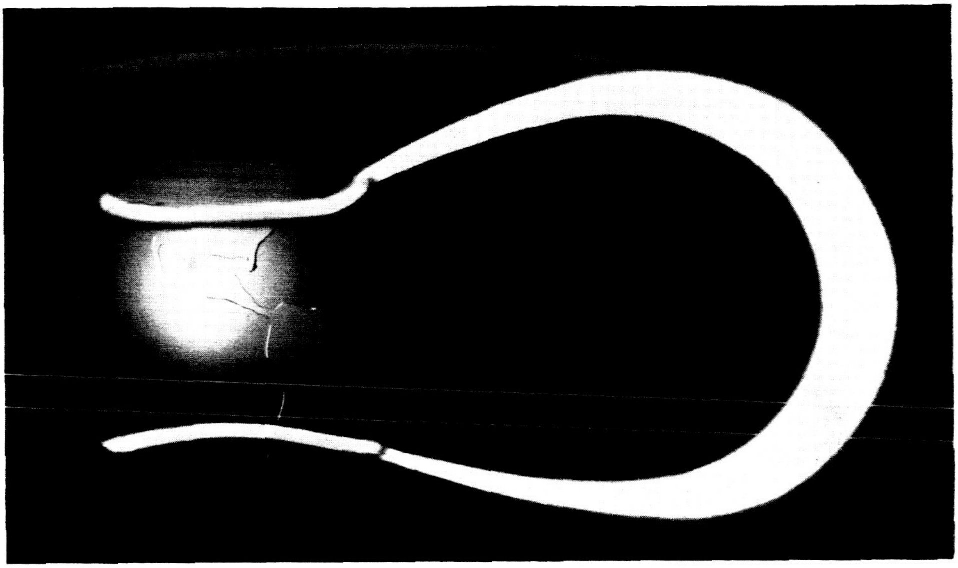

Fig. 8. A lunoid of the radiation belt. This is a volume whose cross section is the region between two neighboring field lines. The lines on the earth at the base of the lunoid are lines of constant integral invarient which represent the loci of the loss zones for the particles in the lunoid.

D we can determine the total loss rate L from the radiation belt by

$$L = \oint D da.$$

To get L we integrate D along two lines of constant integral invarient I, one in the northern Hemisphere and one in the Southern Hemisphere. This sums up the loss from one "lunoid" of the belt (see fig. 8). A lunoid is a figure of revolution whose cross section is a lune, the region between two neighboring field lines, as shown in fig. 8. We will take two strips 1 cm wide around the earth in order to evaluate L. The volume of the lunoid whose base is 1 cm wide for $r_0 = 2.8\ r_e$ is $V = 1.4 \times 10^{20}$ cm^3. L evaluated this way is 2.5×10^7 electrons/sec and the volume loss rate is $l = L/V = 1.5 \times 10^{-13}$ electrons/cm^3 sec. The only contribution to the integral to get L is from the region of South Atlantic. For a steady state situation the volume loss rate $l = s$, the source strength, that is populating the radiation belt. The source strength s calculated [12] for neutron decay is about $\sim 10^{-13}$ elec/cm^3 sec for the outer belt. This value of s looks very similar to the calculated value of l which indicates that the neutron decay source seems adequate in strength to produce the outer belt electrons.

We can also get from this the average residence time τ of an electron in the radiation belt by assuming steady state and using $L = Q/\tau$ where Q is the total number of electrons in the lunoid

$$Q = \left[\frac{10^7 \text{ elec/cm}^2 \text{ sec}}{(2 \times 10^{10} \text{ cm/sec})}\right] 1.4 \times 10^{20} \text{ cm}^3 = 0.7 \times 10^{17} \text{ electrons.}$$

We get for $\tau = Q/L = 0.7 \times 10^{17}/2.5 \times 10^7 = 3 \times 10^9$ sec. This time τ is about the same as the estimates of lifetimes [13, 14, 15] for outer belt electrons, based on coulomb scattering.

It is somewhat surprising that the loss rate is as small as it seems to be as the result of this calculation. We might expect, on the basis of other experiments, that polar-cap neutrons would substantially increase the galactic cosmic ray produced neutron source strength. If this were the case, the source strength would be increased above the value of $s = 10^{-13}$.

4. Comparison of other experiments with the Discoverer results

One other experiment measures the outer belt electron loss rate directly and can be compared with our calculation. The count rate of the 213 GM counter on the Injun satellite [16] determines the electron loss rate of electrons of energy $E > 40$ keV. The angular distribution of the particles observed by this counter over North America is sometimes so wide that the particles are obviously being lost directly into the atmosphere. The loss rate from these observations is much larger than the value calculated here. The average residence time τ of an outer belt electron according to the Injun analysis is about 10^4 seconds. The loss of electrons as observed on Injun must be considered to be the result of a catastrophic process; that is, the electron mirror altitude is changed by a large amount in a single bounce period. This must be due to some process other than coulomb scattering.

This comparison of Injun and Discoverer results seems inconsistent, but with the help of the electron spectrometer experiment [3] on Discoverer we can understand both experiments.

The spectrometer detects three different and distinct spectra of electrons.

Spectrum (A) is a very sharply falling off function of energy. The intensity decreases a factor of e with increase in about 5 keV and is only present below 125 keV. This spectrum is seen almost world wide at some times and other times is not seen at all. Fluxes greater than 10^6 elec/cm^2 sec sr are seen in a 28 keV wide channel centered at 94 keV at some times.

Spectrum (B) e-folds with a change of energy of from 25 to 40 keV and goes up to about 200 keV. It is seen prominently in the auroral zone and shows large time fluctuations. A group of particles of $90 < E < 245$ keV, with similar energy spectrum, with considerably lower intensity is seen in the inner belt loss zone off Brazil and is seen some in the outer belt loss zone off Capetown.

Spectrum (C) usually has a maximum intensity at about 600 keV and goes up beyond 1.2 MeV. At 200 keV it is down about $\times 2$ from maximum intensity. This spectrum is always seen in the inner belt loss zone off Brazil and with lower intensity in the outer belt loss zone off Capetown. The fact that the spectrometer has lower intensities of the (C) spectrum in the outer belt loss zone than off Brazil may be due to the fact that the look direction of the spectrometer is closer to the direction of the field line. If the angular distribution is pancake shaped, it would be seen less near the direction of the field line. The (C) spectrum is also seen in certain small areas of the Pacific Ocean. It shows a smooth spacial variation and is quite constant in time. The intensity at one place normally is constant to a factor of $\times 2$ for long periods.

The fact that there are three different spectra of electrons apparently produced by different processes helps explain other experiments. The Injun experiment [16] that observed catastrophic dumping over North America is quite consistent in spacial extent, time variations and energy and flux with the spectrum (A) of electrons seen on Discoverer. The fact that these electrons are almost all of $E<100$ keV means that the CsI detector on Discoverer will not see these particles.

The (C) spectrum observed on Discoverer looks quite like the equilibrium electron energy spectrum expected [17, 18, 19] from neutron β-decay, except that it extends to higher energies. This spectrum is rather similar to the outer belt electron spectrum seen [20] on Explorer XII in that it is quite flat at about 100 keV and extends up beyond 1 MeV. This population of particles shows smooth spacial variations and roll modulation indicating the particles are trapped, and the flux is quite constant in time. All of these facts and also the fact that this spectrum is seen essentially only in the magnetic field anomalies in the South Atlantic strongly indicates that these particles are being lost by coulomb scattering. If other processes were responsible for the particle loss then there would be no reason for the measured flux to be largest in the South Atlantic. The fact that the fluxes of the (C) spectrum are concentrated in the South Atlantic strongly indicates that the atmosphere controls the loss process. The particles' mirror points come closest to the earth in this region and the particles encounter the densest atmosphere here. This shows coulomb scattering is the dominent loss process.

One other experiment has given information on the loss of electrons from the outer radiation belt. Cladis and Dessler [7] analyzed the results of the experiment of Walt *et al.* [21] who flew a magnetic spectrometer to 1000 km to measure electrons. A drift flux D was obtained from this analysis of 320 electrons/cm^2 sec. Assuming the magnetic anomaly is 1000 km wide, this gives a loss rate of

$$L = 3 \times 10^{10} \text{ electrons/sec.}$$

This is $\times 1000$ larger than the loss rate obtained in this present paper. It is not understood what the difference in these values of L is due to. The electron energy spectrum measured by Walt *et al.* [21] is not very similar to the C spectrum seen by Discoverer over the South Atlantic. It more resembles the B spectrum. Maybe the Walt experiment was not seeing trapped outer belt electrons [20], but some population more like the Injun electrons. This question cannot be answered now, and we have to leave this question about the difference of the L values unsolved.

5. Conclusions

The following points have come out of this analysis:

(1) There are three separate groups of electrons observed on the Discoverer flights.

(2) The (A) spectrum falls off sharply with energy and does not extend above 125 keV. It shows large time fluctuations. The Injun experiment that observed direct dumping was quite likely seeing this flux of particles. The source of these particles is not understood.

(3) The (B) spectrum is the spectrum of auroral electrons. A similar spectrum also appears some in the particles lost from the radiation belts indicating that some of the electrons of $E < 200$ keV in the radiation belt may have been accelerated by auroral processes.

(4) Most of the electrons in the radiation belt are of the (C) spectrum type which looks rather like a neutron β-decay spectrum except extending to higher energies. These particles are lost from the radiation belt by coulomb scattering.

(5) The average residence time of an electron in the outer radiation belt is calculated on the basis of coulomb scattering to be 3×10^9 seconds. The analysis here is uncertain to $\times 2$ or more in two or three instances, but the results are probably good to a factor of $\times 5$.

(6) The data on the (C) spectrum electrons concerning their loss rate and lifetime are all consistent with these particles being the result of neutron decay. These particles constitute most of the inner and outer radiation belt electrons.

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